**Early spectra:**

hydrogen features

*yes* / *no*

SN II      SN I

lightcurve decay     silicon features    *no* → helium features

plateau–phase / linear      *yes*      *yes* / *no*

SN II–P     SN II–L     SN Ia      SN Ib     SN Ic

TYPE 1A Spectrum

silicon II
cobalt II
magnesium II
silicon II
iron II
calcium II
potassium
silicon II
oxygen I
calcium II

4000    5000    6000    7000    8000

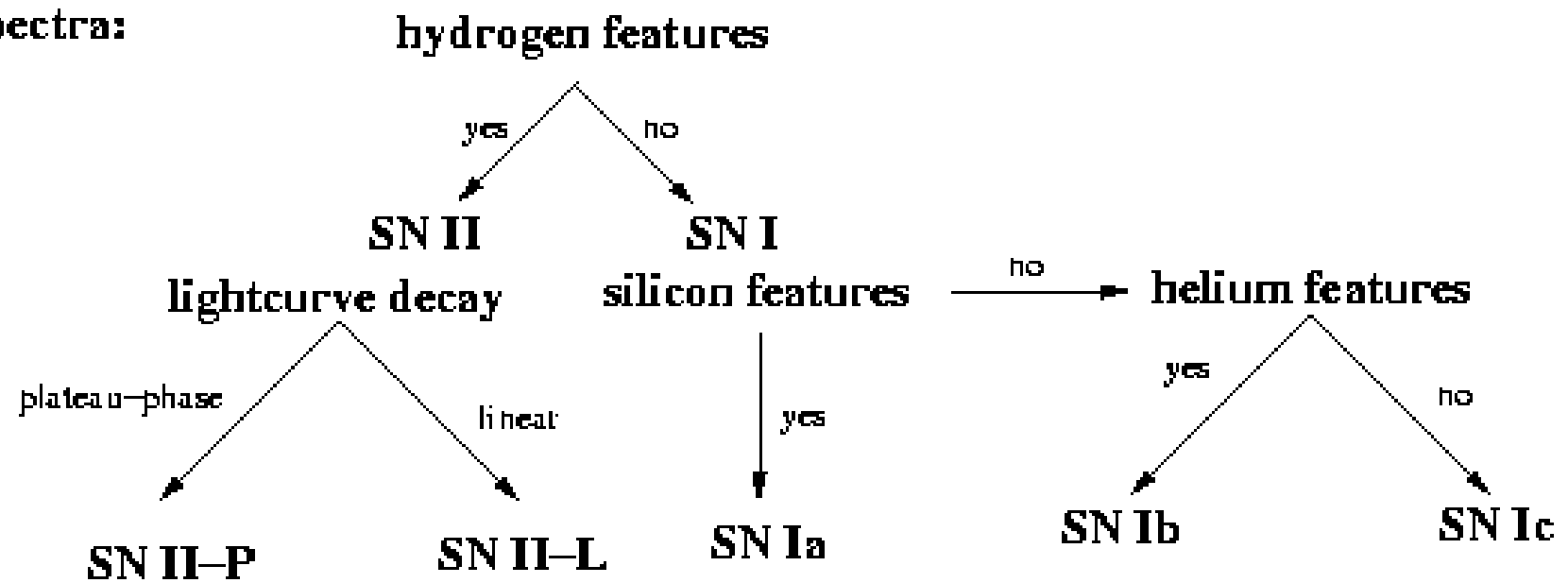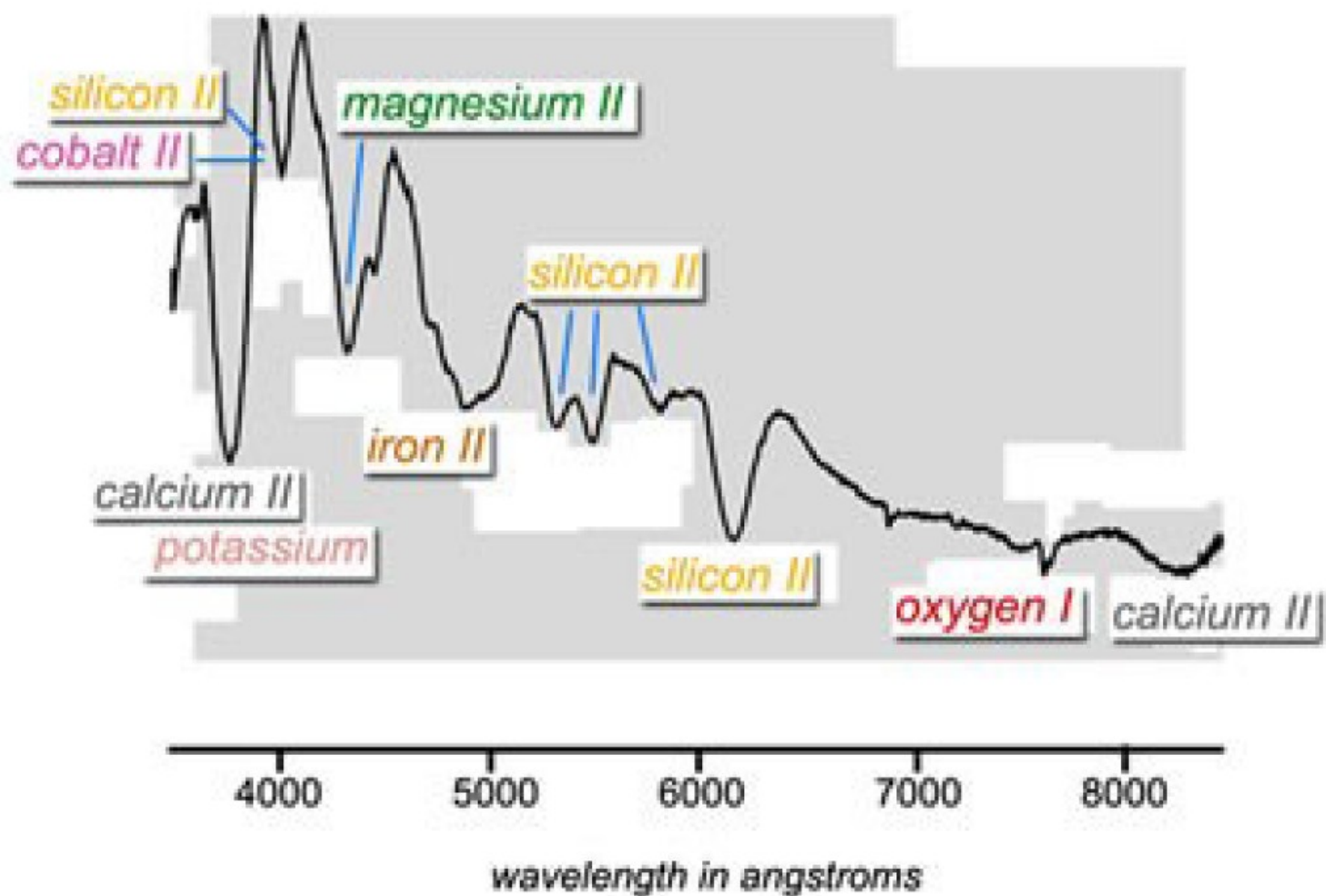wavelength in angstroms

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# Classification

As part of the attempt to understand supernovae, astronomers have classified them according to the absorption lines of different chemical elements that appear in their spectra. The first element for a division is the presence or absence of a line caused by hydrogen. If a supernova's spectrum contains a line of hydrogen (known as the Balmer series in the visual portion of the spectrum) it is classified Type II; otherwise it is Type I. Among those types, there are subdivisions according to the presence of lines from other elements and the shape of the light curve (a graph of the supernova's apparent magnitude versus time).[33]

Supernova taxonomy[34] Type    Characteristics
Type I
Type Ia    Lacks hydrogen and presents a singly-ionized silicon (Si II) line at 615.0 nm (nanometers), near peak light.
Type Ib    Non-ionized helium (He I) line at 587.6 nm and no strong silicon absorption feature near 615 nm.
Type Ic    Weak or no helium lines and no strong silicon absorption feature near 615 nm.

Type II
Type IIP    Reaches a "plateau" in its light curve
Type IIL    Displays a "linear" decrease in its light curve (linear in magnitude versus time).[35]

The supernovae of Type II can also be sub-divided based on their spectra. While most Type II supernova show very broad emission lines which indicate expansion velocities of many thousands of kilometres per second, some have relatively narrow features. These are called Type IIn, where the 'n' stands for 'narrow'. Supernovae that do not fit into the normal classifications are designated peculiar, or 'pec'.[34]

A few supernovae, such as SN 1987K and SN 1993J, appear to change types: they show lines of hydrogen at early times, but, over a period of weeks to months, become dominated by lines of helium. The term "Type IIb" is used to describe the combination of features normally associated with Types II and Ib.[34]

## Type Ia
Main article: Type Ia supernova

## There are several means by which a supernova of this type can form, but they share a

common underlying mechanism. If a carbon-oxygen[nb 2] white dwarf accreted enough matter to reach the Chandrasekhar limit of about 1.38 solar masses[4] (for a non-rotating star), it would no longer be able to support the bulk of its plasma through electron degeneracy pressure[36][37] and would begin to collapse. However, the current view is that this limit is not normally attained; increasing temperature and density inside the core ignite carbon fusion as the star approaches the limit (to within about 1%[38]), before collapse is initiated.[4] Within a few seconds, a substantial fraction of the matter in the white dwarf undergoes nuclear fusion, releasing enough energy (1–2 × 10⁴⁴ joules)[39] to unbind the star in a supernova explosion.[40] An outwardly expanding shock wave is generated, with matter reaching velocities on the order of 5,000–20,000 km/s, or roughly 3% of the speed of light. There is also a significant increase in luminosity, reaching an absolute magnitude of -19.3 (or 5 billion times brighter than the Sun), with little variation.[41]

One model for the formation of this category of supernova is a close binary star system. The larger of the two stars is the first to evolve off the main sequence, and it expands to form a red giant.[42] The two stars now share a common envelope, causing their mutual orbit to shrink. The giant star then sheds most of its envelope, losing mass until it can no longer continue nuclear fusion. At this point it becomes a white dwarf star, composed primarily of carbon and oxygen.[43][44] Eventually the secondary star also evolves off the main sequence to form a red giant. Matter from the giant is accreted by the white dwarf, causing the latter to increase in mass.

Another model for the formation of a Type Ia explosion involves the merger of two white dwarf stars, with the combined mass momentarily exceeding the Chandrasekhar limit.[45] A white dwarf could also accrete matter from other types of companions, including a main sequence star (if the orbit is sufficiently close).

Type Ia supernovae follow a characteristic light curve—the graph of luminosity as a function of time—after the explosion. This luminosity is generated by the radioactive decay of nickel-56 through cobalt-56 to iron-56.[41] The peak luminosity of the light curve was believed to be consistent across Type Ia supernovae (the vast majority of which are initiated with a uniform mass via the accretion mechanism), having a maximum absolute magnitude of about -19.3. This would allow them to be used as a secondary[46] standard candle to measure the distance to their host galaxies.[47] However, recent discoveries reveal that there is some evolution in the average lightcurve width, and thus in the intrinsic luminosity of Supernovae, although significant evolution is found only over a large redshift baseline.[48]

Type Ib and Ic
Main article: Type Ib and Ic supernovae
SN 2008D, a Type Ib[49] supernova, shown in X-ray (left) and visible light (right) at the far upper end of the galaxy. NASA image.[50]

These events, like supernovae of Type II, are probably massive stars running out of fuel at their centers; however, the progenitors of Types Ib and Ic have lost most of their outer (hydrogen) envelopes due to strong stellar winds or else from interaction with a companion.[51] Type Ib supernovae are thought to be the result of the collapse of a massive Wolf-Rayet star. There is some evidence that a few percent of the Type Ic supernovae may be the progenitors of gamma ray bursts (GRB), though it is also believed that any hydrogen-stripped, Type Ib or Ic supernova could be a GRB, dependent upon the geometry of the explosion.[52]

## Type II

Main article: Type II supernova

The onion-like layers of a massive, evolved star just prior to core collapse. (Not to scale.)

Stars with at least nine solar masses of material evolve in a complex fashion.[5] In the core of the star, hydrogen is fused into helium and the thermal energy released creates an outward pressure, which maintains the core in hydrostatic equilibrium and prevents collapse.

When the core's supply of hydrogen is exhausted, this outward pressure is no longer created. The core begins to collapse, causing a rise in temperature and pressure which becomes great enough to ignite the helium and start a helium-to-carbon fusion cycle, creating sufficient outward pressure to halt the collapse. The core expands and cools slightly, with a hydrogen-fusion outer layer, and a hotter, higher pressure, helium-fusion center. (Other elements such as magnesium, sulfur and calcium are also created and in some cases burned in these further reactions.)

This process repeats several times, and each time the core collapses and the collapse is halted by the ignition of a further process involving more massive nuclei and higher temperatures and pressures. Each layer is prevented from collapse by the heat and outward pressure of the fusion process in the next layer inward; each layer also burns hotter and quicker than the previous one – the final burn of silicon to nickel consumes its fuel in around one day, or a few days.[53] The star becomes layered like an onion, with the burning of more easily fused elements occurring in larger shells.[54][55]

In the later stages, increasingly heavier elements undergo nuclear fusion, and the binding energy of the relevant nuclei increases. Fusion produces progressively lower levels of energy, and also at higher core energies photodisintegration and electron capture occur which cause energy loss in the core and a general acceleration of the fusion processes to maintain equilibrium.[53] This escalation culminates with the production of nickel-56, which is unable to produce energy through fusion (but does produce iron-56 through radioactive decay).[56] As a result, a nickel-iron core[57] builds up that cannot produce any further outward pressure on a scale needed to support the rest of the structure. It can only support the overlaying mass of the star through the degeneracy pressure of electrons in the core. If the star is sufficiently large, then the iron-nickel core will eventually exceed the Chandrasekhar limit (1.38 solar masses), at which point this mechanism catastrophically fails. The forces holding atomic nuclei apart in the innermost layer of the core suddenly give way, the core implodes due to its own mass, and no further fusion process can ignite or prevent collapse this time.[36]

## Core collapse

See also: Gravitational collapse

The core collapses in on itself with velocities reaching 70,000 km/s (0.23c),[58] resulting in a rapid increase in temperature and density. The energy loss processes operating in the core cease to be in equilibrium. Through photodisintegration, gamma rays decompose iron into helium nuclei and free neutrons, absorbing energy, whilst electrons and protons merge via electron capture, producing neutrons and electron neutrinos which escape.

In a typical Type II supernova, the newly formed neutron core has an initial temperature of about 100 billion kelvin (100 GK); 6000 times the temperature of the sun's core. Much of this thermal energy must be shed for a stable neutron star to form (otherwise the neutrons would "boil away"), and this is accomplished by a further release of neutrinos.[59] These 'thermal' neutrinos form as neutrino-antineutrino pairs of all flavors, and total several times the number of electron-capture neutrinos.[60] About 1046 joules of gravitational energy—approximately 10% of the star's rest mass—is converted into a ten-second burst of neutrinos; the main output of the event.[53][61] These carry away energy from the core and accelerate the collapse, while some neutrinos may be later absorbed by the star's outer layers to provide energy to the supernova explosion.[62]

The inner core eventually reaches typically 30 km diameter,[53] and a density comparable to that of an atomic nucleus, and further collapse is abruptly stopped by strong force interactions and by degeneracy pressure of neutrons. The infalling matter, suddenly halted, rebounds, producing a shock wave that propagates outward. Computer simulations indicate that this expanding shock does not directly cause the supernova explosion;[53] rather, it stalls within milliseconds[63] in the outer core as energy is lost through the dissociation of heavy elements, and a process that is not clearly understood is necessary to allow the outer layers of the core to reabsorb around 1044 joules[nb 3] (1 foe) of energy, producing the visible explosion.[64] Current research focuses upon a combination of neutrino reheating, rotational and magnetic effects as the basis for this process.[53]

When the progenitor star is below about 20 solar masses (depending on the strength of the explosion and the amount of material that falls back), the degenerate remnant of a core collapse is a neutron star.[58] Above this mass the remnant collapses to form a black hole.[55][65] (This type of collapse is one of many candidate explanations for gamma ray bursts—producing a large burst of gamma rays through a still theoretical hypernova explosion.)[66] The theoretical limiting mass for this type of core collapse scenario was estimated around 40–50 solar masses.

Above 50 solar masses, stars were believed to collapse directly into a black hole without forming a supernova explosion,[67] although uncertainties in models of supernova collapse make accurate calculation of these limits difficult. In fact recent evidence has shown stars in the range of about 140–250 solar masses, with a relatively low proportion of elements more massive than helium, may be capable of forming pair-instability supernovae without leaving behind a black hole remnant. This rare type of supernova is formed by an alternate mechanism (partially analogous to that of Type Ia explosions) that does not require an iron core. An example is the Type II supernova SN 2006gy, with an estimated 150 solar masses, that demonstrated the explosion of such a massive star differed fundamentally from previous theoretical predictions.[68][69]